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An archaeometric contribution to the study of ancient millstones from the Mulargia area (Sardinia, Italy) through new analytical data on volcanic raw material and archaeological items from Hellenistic and Roman North Africa

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A B S T R A C T

The main quarrying area of the Mulargia ignimbrite, used mainly to produce rotary millstones during the Hellenistic and Roman age, has been identified and sampled in order to update and complete the petrographic and geochemical database by employing standard analytical methods (optical microscopy and ICP-AES/MS spectrometry). The combination of petrographic and geochemical data concerning the Tertiary rhyodacitic to rhyolitic ignimbrites outcropping in central west Sardinia, previously very poor, form a helpful tool for future work on this important typology of volcanic millstones. The data bank obtained has been used to verify the geological source of eight millstones discovered in different rural settlements of Hellenistic Numidia and Roman Africa Proconsularis supposed by archaeologists to be made of ignimbrite from Mulargia. The results of the petro-archaeometric study confirmed a Sardinian origin for these millstones and represent one of the very few analytical proofs of their effective export to North Africa.

1. Background and aims

Most of the Hellenistic and Roman millstones and rotary querns found in archaeological sites throughout the Mediterranean are made of vesicular volcanic rock – grey basic to intermediate lavas, a characteristic leucite-phyric lava, and a distinctive reddish-brownish rhyo-dacitic ignimbrite are among the most widespread in the overall basin (see for example Peacock, 1980, 1986, 1989; Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989, 1990, 1991, 1993; Lorenzoni et al., 1996, 2000a, b; Oliva et al., 1999; Antonelli et al., 2000, 2001, 2004, 2005; Buffone et al., 2003; Renzulli et al., 2002; Santi et al., 2004; Santi et al., 2013; Antonelli and Lazzarini, 2010 and reference therein; Antonelli and Lazzarini, 2012; de Vos et al., 2011) – the sources of which are mainly located in Italy (*e.g.* Mt. Etna in Sicily, Somma-Vesuvius in Campania, the Volsini-Orvieto region in Latium, Mulargia in Sardinia and the Euganean Hills in the Veneto).

During the Roman age, Sardinia was an important grain provider for Rome so it also became an active millstone production and trade centre. The archaeological and archaeometric studies of Hellenistic and Roman donkey millstones on the island revealed that the rotary mill made of an upper not reversible (Morgantina-type; Fig. 1) or reversible (hourglass shaped) stone (*catillus*) resting on the conical lower stone (*meta*) is the most common type, whereas cylindrical hand querns are quite rare (Williams-Thorpe and Thorpe,

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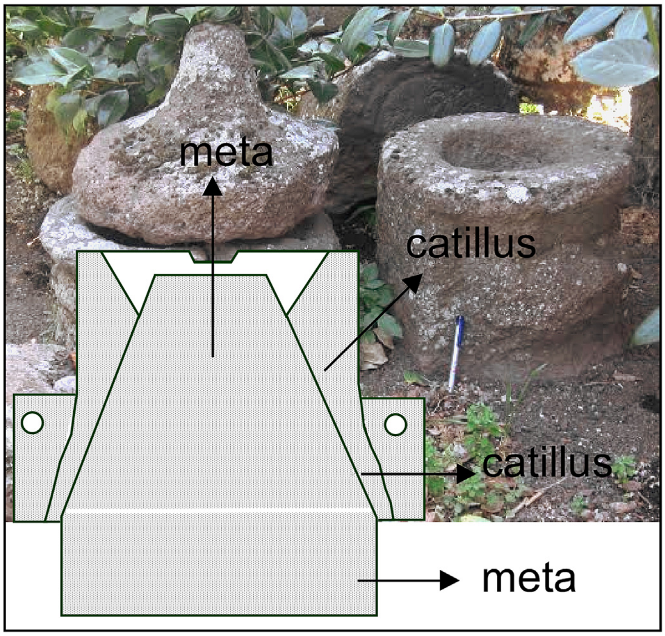

Fig. 1. Fragments of lower (*meta*) and upper (*catillus*) stones of Hellenistic Mulargia rotary millstones, now exhibited in the garden of a private house at the village.

1989). Quoting from Williams-Thorpe and Thorpe (1989), the great majority of these items are made of a reddish-brown ignimbrite of acid chemical composition from a single source of Oligocene-Miocene volcanics cropping out at Mulargia (called *Molaria* in Roman times; Meloni, 1975), a village near Macomer (west-central Sardinia, from the end of the VI to the III century BC under Carthaginian domination; Fig. 2) and, to a very minor extent, of grey vesicular subalkaline lavas of basic-intermediate composition from various sources, mainly within the Pliocene-Pleistocene volcanics of the island. However, on the basis of the archaeometric studies (Peacock, 1980; Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989) we can assume that from the 1st century AD only the Mulargia millstone production area was clearly a major source exporting hourglass-shaped mills on a medium Mediterranean scale, particularly towards North–Africa, from Morocco (Volubilis and Tetouan) to Sicily (Segesta, Solunto, Selinunte and Megara Iblea) passing through Spain (Ampurias and Mallorca), Algeria (Djemila) and Tunisia (Utica, Carthage, Musti, Sousse and Gightis) (Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989; Antonelli and Lazzarini, 2010; de Vos et al., 2011).

This ignimbrite has a distinctive red-brown colour with paler *fiammae* and contains many sharp edged vesicles (usually about 1–5 mm in size) very often lined with characteristic green phyllosilicate phases (Fig. 3). Unfortunately, by virtue of its general macroscopic aspect, most archaeologists suppose that in-hand specimens can be identified with the naked eye; consequently, until now, mineralogical and petrochemical data on both the quarry material and millstones have been available only for very few samples (Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989). In fact, even the fundamental work carried out by Williams-Thorpe and Thorpe (1989) on the provenance and archaeology of Roman millstones from Sardinia provides complete geochemical analyses for only two field samples coming from outcrops and disturbed ground to the south of the village of Mulargia – the actual quarry was not found – while complete chemical data for only one Mulargia millstone found outside Sardinia or Italy are currently available in the literature (as a matter of fact Williams-Thorpe, 1988; states that she analysed two Mulargia mills found at Ampurias and two others found at Carthage, but she presents the results of one sample only, and all of the Roman millstones analysed by Williams-Thorpe and Thorpe, 1989; were found in Sardinia).

The aim of this work was (i) to identify clearly the location of the ancient quarrying area of Mulargia ignimbrite, (ii) to provide a complete petrochemical database of the rocks, useful for archaeometric purposes, and (iii) to compare it with similar data produced for some Roman millstones discovered in various rural settlements located not far from the ancient towns of Thugga and Thibursicum Bure (today Dougga and Teboursouk, respectively), in the Tunisian High Tell.

2. Geological setting

2.1. Oligo-Miocene Sardinian volcanism

The Mulargia ignimbrites belong to the Oligo-Miocenic volcanic cycle of Sardinia (33–11 My; Beccaluva et al., 1985), with a time span of about 20 My (Marchi et al., 2002), whose products are widely used as building stones in large areas of the island. This volcanism is generally placed in connection with a subduction zone, with dipping NW or N-NW, parallel to the European continental paleo-margin (Coulon, 1977; Savelli et al., 1979; Beccaluva et al., 1985, 1989). The Oligo-Miocenic volcanic cycle of Sardinia falls within a geological context characterized by intense activity that gave place to the translation and rotation of the Sardinia–Corsica microplate from its original position (oriented NE–SW) to the current one oriented approximately NS, with the formation of the Balearic back-arc basin (Dostal et al., 1982; Peccerillo, 2005). This activity led, during the Oligocene, to the formation of the rift between Sardinia and Provence (Cherchi and Montadert, 1982; Burrus, 1984; Cherchi et al., 2008) and subsequently the "Fossa Sarda" (Vardabasso, 1963) with a complex graben structure that extends in the central-western part of Sardinia from the Gulf of Asinara (in the north) to the Gulf of Cagliari (in the south; Fig. 2).

The genesis of Sardinian Oligo-Miocene volcanism may be related to metasomatism of the mantle wedge by hydrous liquids and/or fluids whose composition is probably linked to the varying depths of the subduction slab, greater to the north than to the south (Beccaluva et al., 1989). This volcanism shows a calcalkaline affinity *l.s.* varying from tholeiitic (minor) to calcalkaline *s.s.* (mainly), to high-k calcalkaline and shoshonitic (Beccaluva et al., 1989, 1994). The products of this petrographic province have different geochemical characters in different parts of the island, on average, with a higher content of K_2O to the north, though the highest known values are present in pyroclastics outcropping in central Sardinia, near Lake Omodeo. The greatest quantities of high-K pyroclastics are located in the Oschiri-Chilivani area (northern Logudoro, central-northern Sardinia; Columbu et al., 2011 and reference therein). In NW Sardinia less evolved products (lava) have a predominantly Na-affinity, while the more evolved ones (pyroclastics) are potassic, and those of the Macomer area have a high-K calcalkaline affinity. In central Sardinia volcanics are essentially potassic to high potassic. Finally, the south of Sardinia features a different context and, apart from rare exceptions, pyroclastic products exhibit sodic (*e.g.*, sector-Cixerri Pula) and potassic (*e.g.*, San Pietro island) affinity.

The climax of the volcanic activity goes back to a period between 23 and 17 My (Savelli et al., 1979). In this geological period in various parts of the island, but mainly along the graben structure, highly explosive fissural activity, simultaneously and in alternation with andesitic and basaltic lavas, produced abundant pyroclastic and lava flows with dacitic-rhyolitic composition.

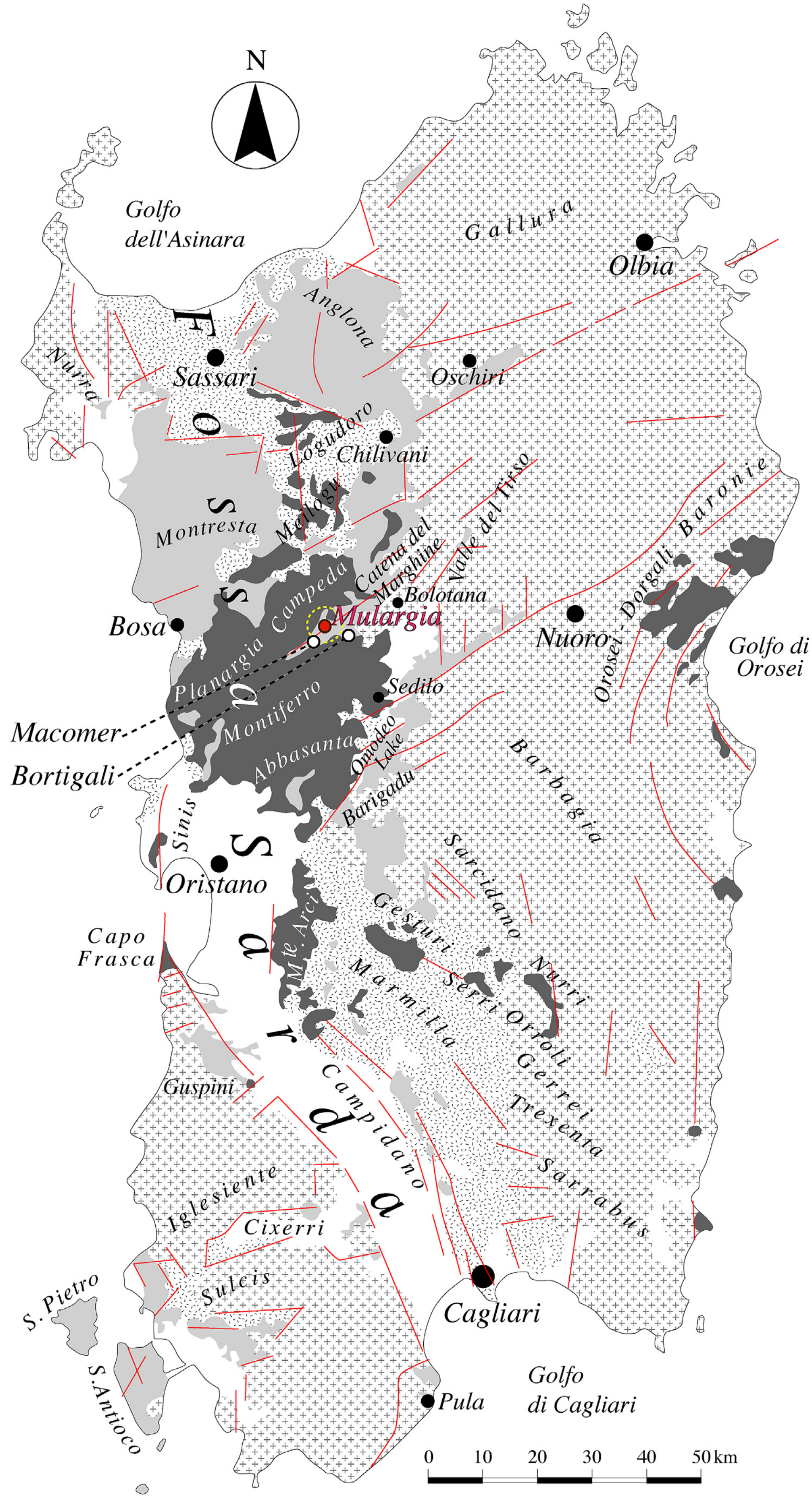

Fig. 2. Schematic geological map of Sardinia and localization of the village of Mulargia. Legend of patterns and colours referred to lithologies: white = recent alluvial sediments; light grey = Oligo-Miocene volcanics including the "Mulargia ignimbrite"; dark grey = Plio-Pleistocene volcanics; stippled grey = Miocene marine sediments; grey crosses = Palaeozoic crystalline basement and Mesozoic formations; red continuous and dashed lines = faults. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Macroscopic aspect of the vesicular reddish ignimbrite from Mulargia, with typical green mineral deposits (celadonite) in the vesicles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Volcanic district of Mulargia-Macomer-Bortigali

The Mulargia-Macomer-Bortigali volcanic district (Guarino et al., 2011) extends in a wide area around the three villages, including the north area of Macomer, where volcanics belonging mainly to the Oligo-Miocenic cycle and, to a lesser extent, to the Plio-Quaternary cycle outcrop with variable composition (Fig. 2).

This district belongs to a regional structure called “Catena del Marghine” (Chain of Marghine), formed in the north by a tectonic *horst* elongated along the NE–SW direction, which is bordered on the west by the Plio-Quaternary plateau of the Planargia (Porcu, 1983). The “Catena del Marghine” is the element of separation between the Plio-Quaternary basaltic plateaux of Abbasanta and those of the high Planargia-Campeda.

However, most of the outcrops of the district can be referred to Oligo-Miocenic volcanism activity (~22–21 My; Savelli et al., 1979; Beccaluva et al., 1985; Lecca et al., 1997) whose volcanics constitute vast outcrops (often consisting of several overlapping cooling units) stratigraphically alternating with rhyolitic lava flows and welded to unwelded ignimbrites. Volcanics were emplaced in subaerial, transitional and marine environments at the edges of the Miocene sea basin of the “Fossa Sarda”.

The volcanic sequence of the Macomer area, bounded on the south by the Silanus-Benetutti fault zone, has a thickness of about 500 m (Assorgia et al., 1995) and emerges continuously from the village of Bortigali (to the south of the Marghine fault) to Mt. “Santu Padre” (immediately to the north of Bortigali), to Mulargia village; this volcanic sequence decreases in thickness north-westward where is covered by the Campeda Plio-Quaternary basaltic expansions (Lecca et al., 1997).

Conversely, to the east, in the Bolotana-Sedilo area, characterized by a significant low gravimetry anomaly, the maximum cumulative thickness of Oligo-Miocene volcanic rocks can reach several hundred metres (800–1000 m; Andriani et al., 2001). According to Lecca et al., 1997, the stratigraphic succession of the Macomer area, from the bottom upwards, is as follows:

a) densely welded ignimbrites with dacitic composition;
b) thin and discontinuous level of poorly welded ash and pumice flows and related epiclastites;
c) densely welded ignimbrites (*e.g.*, ignimbrites at the top of Monte Santu Padre, to the north of Bortigali), characterized by typical large flattened *fiammae (flames)*;
d) greyish stratified sequence of surge deposits and reddish densely welded (mainly aphyric) ignimbrites.

From a petrochemical point of view, the Oligo-Miocene volcanics of the district are subalkaline rocks with a composition ranging from basaltic andesite to andesite, to dacite, to trachy-dacite, to rhyolite, while the Plio-Quaternary ones belong to the alkaline and transitional volcanic series and show a composition from basaltic trachy-andesite to trachy-andesite, to trachyte (Columbu et al., 2011; references therein and data not published). Fig. 3 shows the compositional distribution of the Oligo-Miocenic ignimbrites from

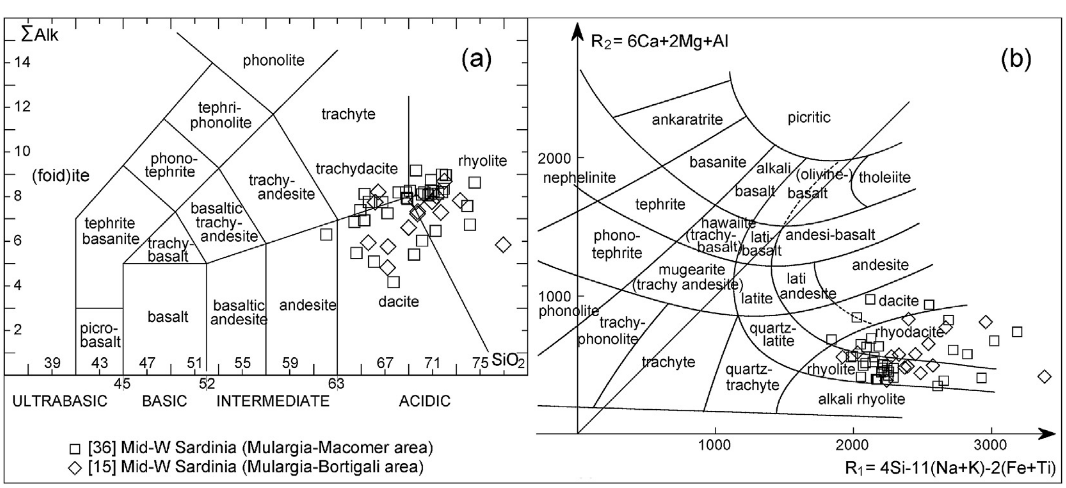

Fig. 4. Classification of the ignimbrites from the Mulargia-Macomer-Bortigali volcanic district using (a) the Total Alkali *vs.* Silica (Le Bas et al., 1986) and (b) R_1 *vs.* R_2 (De La Roche et al., 1980) diagrams. From Columbu et al., 2011, references therein and unpublished data.

the chief areas of Mulargia-Macomer and Mulargia-Bortigali (which are the main concern of the present paper) according to the classification diagrams of Le Bas et al., 1986 and De La Roche et al., 1980.

3. The quarrying area of Mulargia

In the area of the Mulargia village, classically considered the main production centre of Roman millstones in Sardinia (Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989), several ignimbritic products outcrop with a degree of welding varying from medium to high, depending on the composition and mode of emplacement (*e.g.*, temperature, cooling rate and loss of volatile, lithostatic load).

A field survey of the volcanic outcropping around Mulargia enabled three main Miocenic ignimbritic lithotypes to be identified on the basis of their petrographic and volcanological features, as follows:

1) Brown to red-brownish dacites, rhyodacites and rhyolites with porphyritic structure (phenocrysts: Pl ± Opx ± Cpx with rare Qtz, Kfs, Hbl, Bt; hereafter abbreviations are after Kretz, 1983). They exhibit a medium–high degree of welding (*i.e.*, lava-like ignimbrites), a vitrophyric basal level and variable vesiculation (vesicles frequently with Ø ≈ 3–9 mm in major axis); vesicles are often filled with greenish deposits produced by weathering-halmyrolysis processes involving the mobilization, circulation and precipitation of SiO_2 (*e.g.*, crystobalite) as well as chemical-mineralogical transformation of primary silicates in phyllosilicates (*e.g.*, green celadonite, chlorite and montmorillonite phases) and, probably, zeolite minerals. These ignimbrites outcrop

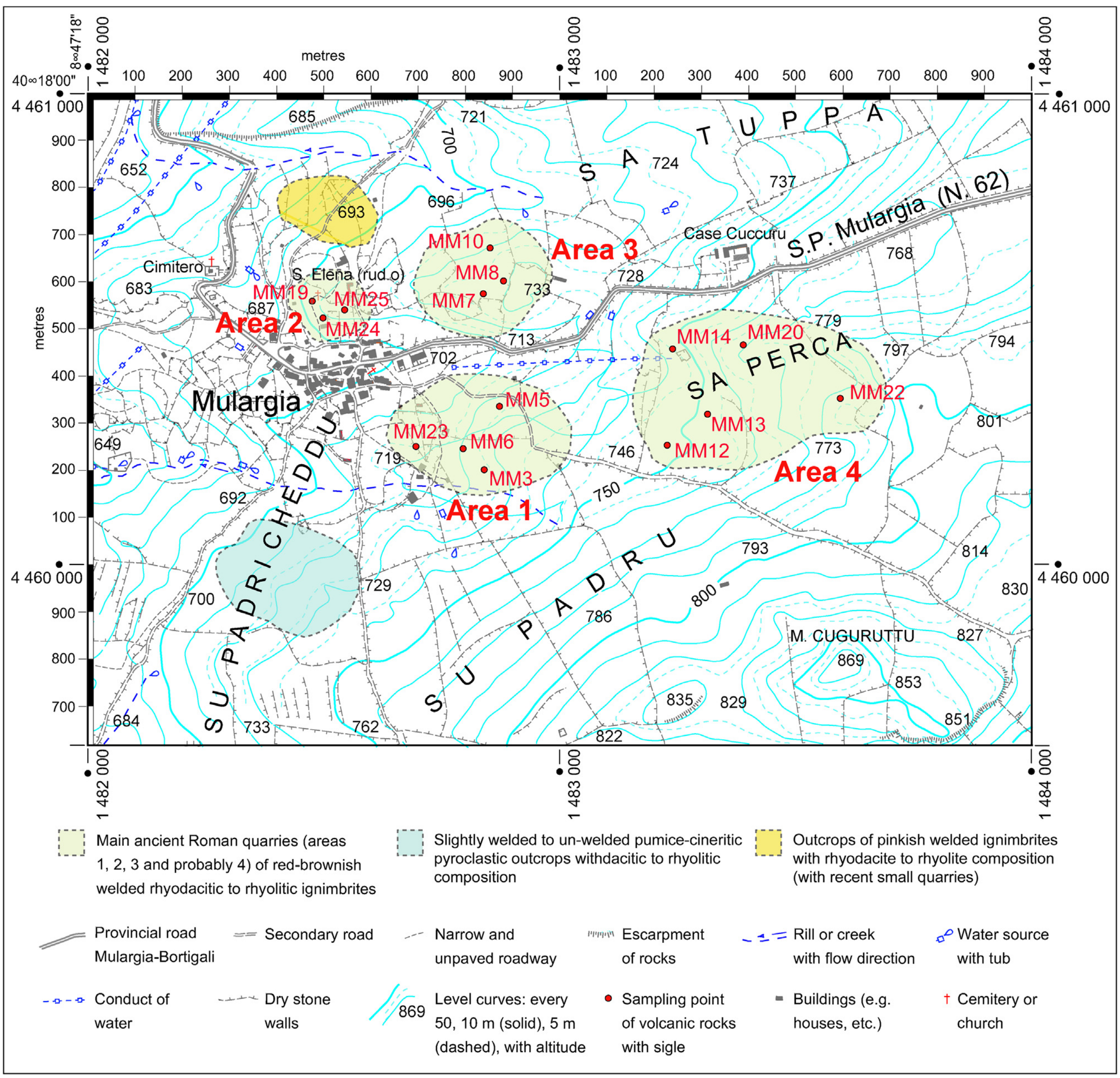

Fig. 5. Sketch map of the area (sides: 2 km, 1.38 km) around the village of Mulargia showing the four ancient quarrying and production district of ignimbrite millstones during the Roman period. Topographic base according to "Carta Tecnica Regionale numerica" (1:10.000) Section No. 498100 – Macomer, "Servizio Informatico e Cartografico" della Regione Autonoma della Sardegna. Coordinates of the U.T.M. (32) system: NW) N – 4 461 000, E –1 482 000 (geographical: N – 40∞18′00″, E – 8∞47′18″); NE) N – 4 461 000, E – 1 484 000; SW) N – 4 459 620, E – 1 482 000; SE) N – 4 459 620, E – 1 484 000. U.T.M. coordinates of the centre of Mulargia are: N – 4 460 425, E – 1 482 535.

Fig. 6. Partial views of the ancient Mulargia quarrying area; (a, b, c): small quarry faces with stepped blocks, wedge-holes and pick marks; (d) a deposit of ancient debris containing small blocks in various stages of shaping; (e) a half-finished *meta* still *in situ* between the locality of *Sa Perca* and the top of *Crastu Littu*; (f) detail of one of the small half-shaped blocks present in the area.

mostly within or all around the village of Mulargia (within a 1 km radius);

2) Pinkish massive dacitic to rhyodacitic ignimbrites showing porphyritic structure (phenocrysts: Pl $\pm$ Opx $\pm$ Cpx), medium–high degree of welding and presence of elongated *fiammae*; they outcrop mainly to the north of the village of Mulargia;
3) Grey-purple-green pumice-cineritic pyroclastites, at times passing to ignimbrite, with variable composition from dacite to rhyolite, a generally low, sometimes medium, degree of welding, which are variegated by the presence of slightly crushed to flattened pumice, cognate fragments, crystal- and xeno-clasts; they outcrop in the southern sector of the Mulargia area.

In general, most of the Oligo-Miocene ignimbrites were significantly used as building materials from the Neolithic (Verdiani and Columbu, 2010; Columbu et al., 2013) to the Roman (Melis and Columbu, 2000) and the Romanesque-Medieval periods (Macciotta et al., 2001; Columbu et al., 2011, 2014; Coroneo and Columbu, 2010). Nevertheless, only “lithotype 1” is macroscopically very similar to the findings of Roman millstones classically supposed to be from Sardinia in the current archaeological literature. All around Mulargia, to the north and south of the village, within a radius of a few hundred metres, several unfinished artefacts (*catilli* and *metae*) and whole hourglass-shaped millstones made of this lithotype were found (some of them are now in the gardens of private houses), confirming that an excavation and manufacturing site of hour-glass millstones existed in antiquity in these same areas. Unfortunately, due to human activities and urbanization that have occurred over time and which have changed the original morphology of the territory, the evidence of the ancient exploitation has almost entirely been lost. Nevertheless, some signs of the ancient quarrying activity have been preserved (Fig. 5). In particular, several deposits of ancient debris that still contain small blocks in various stages of shaping, including fragmentary and whole conical shaped stones, were found in four different areas between Mulargia village and both the *Su Padru* (to the south-east), and *Sa Tuppa* (to the north-east) localities (Figs. 5 and 6a–d); moreover, some half-finished *metae* (h: 55 cm; basal diameter: 40–50 cm; Fig. 6e–f) and a small quarry face with large stepped blocks showing wedge-holes (Fig. 6b, c) and pick marks attesting to ancient exploitation were found at *Sa Perca*, a locality to the east of Mulargia and between this latter and the top of the *Crastu Littu* volcanic structure (at about 800–850 m a.s.l.). On the basis of this clear field evidence concerning an ancient extraction activity of “lithotype 1” we can assume this specific sector of the Mulargia territory was the main quarrying and production area for millstones.

In fact, no similar field proofs have been found as far as lithotypes 2 and 3 are concerned. With reference to the latter, some old quarry fronts were discovered on the western side of the volcanic

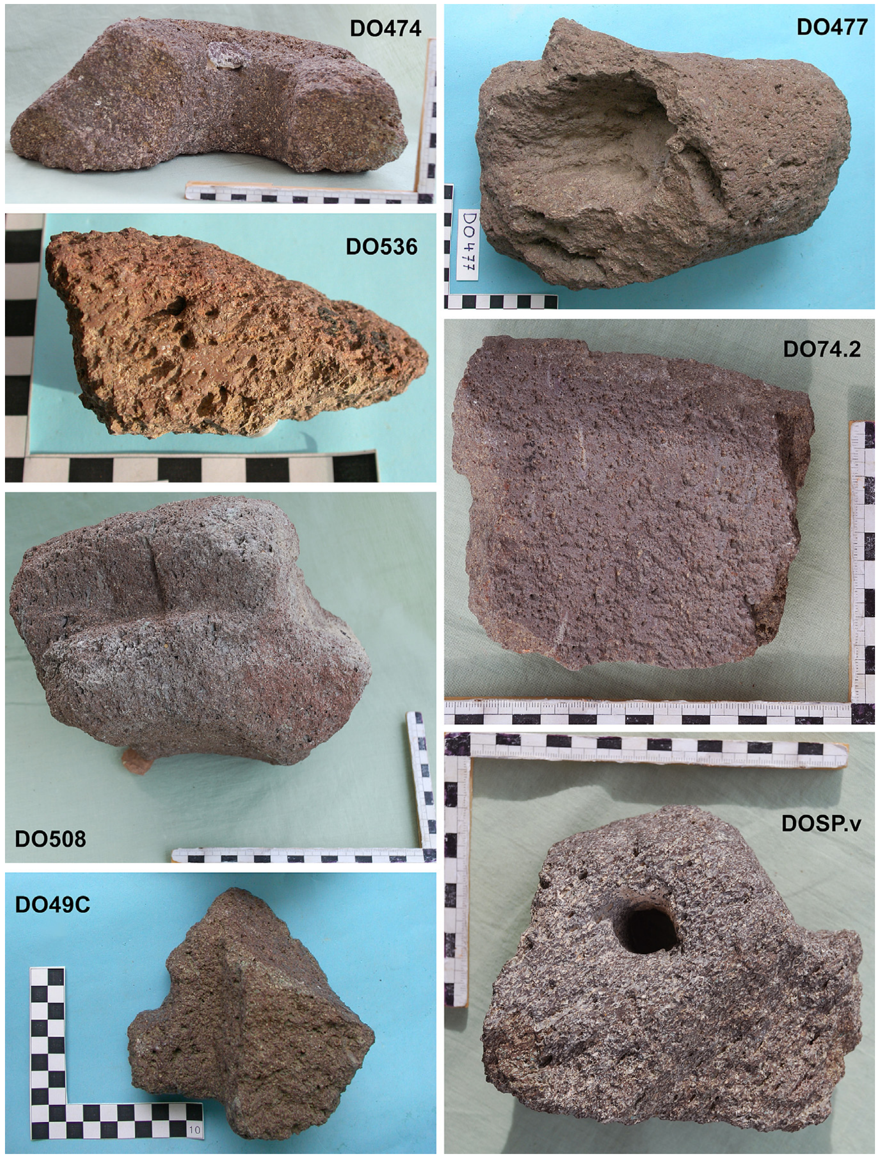

Fig. 7. Seven of the eight Hellenistic and Roman fragmentary mills sampled from ancient rural sites in Tunisia. Typologies are reported in Table 1.

Mt. Cuguruttu, at the "Su Padricheddu" site, at an altitude of between 700 and 750 m above sea level. These fronts are certainly not recent and date back to the Pre-industrial Age, but there are no evaluation elements or archaeological findings to define the exact period of extraction. Anyway, the extraction involved mostly metric blocks of pseudo-prismatic shape and the quarried rock does not present suitable petro-physical features for producing mills.

4. Mills from farms in Africa Proconsularis

The eight mills discussed in this paper (Fig. 7) are part of a substantial group (made of basic, intermediate and acid lavas) found on the surface during the archaeological and topographic survey of the rural sites around Thugga and Thibursicum Bure, today Dougga and Teboursouk, in the Tunisian High Tell conducted from 1994 through 2012. The study of this large group of items and a comparison of their petrological features with those presented by Tunisian and Algerian lavas is currently in progress and will be the object of a forthcoming paper. The survey was conducted by the Institut National du Patrimoine de la Tunisie and the University of Trento, Italy. The research was sponsored by the Italian Foreign Office, by the Italian Ministry of Education, University and Research and by the University of Trento, Department of Humanities (FIRB and PRIN projects).[1]

The region surveyed lies 400–960 m above sea level in the middle Bagradas (now Medjerda) valley, on the south side of the river, some 100 km from the Mediterranean coast (Fig. 8). It has a semi-arid climate, hot summers and an average rainfall of 400–500 mm per year. The landscape is characterized by rolling hills, three valleys and the plateau of Djebel Gorraa (summit altitude 940 m a.s.l.) with many outcrops of nummulitic limestone; the stony slopes are suitable for growing olives. The soil consisting of clay or marl on limestone in the flat fields in the Khalled valley could be used for crops. Intercultivation was probably practiced in antiquity, as it is now.

[1] Preliminar reports: de Vos 2000, 2004; de Vos *et al.*, 2011; de Vos and Attoui 2011; de Vos 2013; de Vos *et al.* 2013.

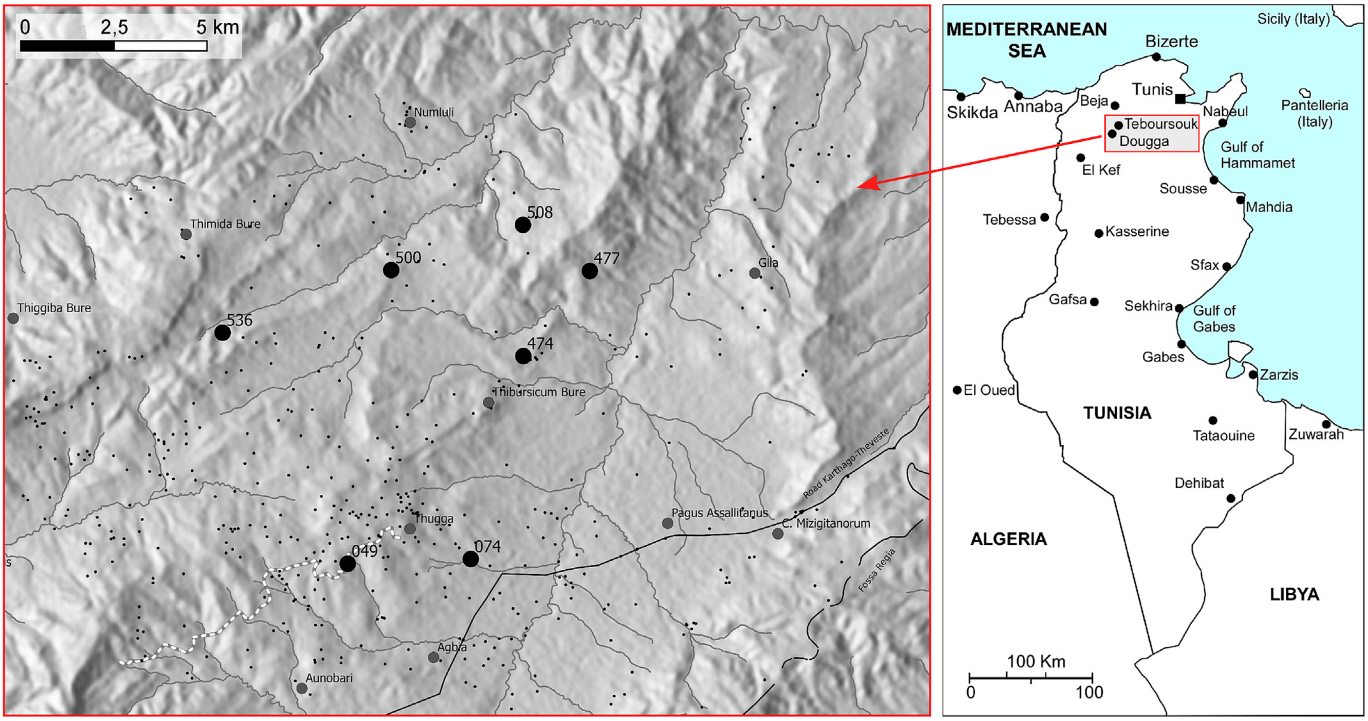

Fig. 8. Tunisia, High Tell, to the south of the River Bagradas (Medjerda): the area surveyed around Thugga (Dougga) and Thibursicum Bure (Teboursouk). Small black dots: rural sites found by survey 1994–2008. Big black dots: rural sites with mill-samples discussed in this paper; places with toponyms; aqueduct with dotted line.

Most likely, the many springs, the limestone bedrock with flint nodules and forests attracted people rapidly and the zone was occupied from the Pre- and Protohistoric periods as can be deduced from stone tools and megalithic tombs, rock cut tombs and tumuli.

The ceramic record of the rural sites contains diagnostic pottery and amphora shards from the 3rd–2nd centuries BC until the 8th century AD and shows a gradual and continuous increase of rural population and agricultural production in the Roman period but major expansion and dynamism took place under Vandal and Byzantine rule (Polla, 2006; de Vos, 2013; Andreoli, 2013). Thugga and Thibursicum Bure lay in the Carthaginian *pertica*, a zone of tax-free cities for Roman citizens, whose territory belonged to Carthage until the reign of Septimius Severus, when Thugga became a *municipium*. The middle Bagradas excels because of seven great inscriptions concerning lease conditions codified by the *lex Hadriana de rudibus agris*.

Table 1
List of the samples of Mulargia ignimbrites from the quarrying areas investigated and from millstones collected from Tunisian archaeological sites, with their localities and geographical coordinates of sampling points.

Samples		Site/type	Location	Geographical coordinates N	Geographical coordinates E
MM3				4 460 200	1 482 835
MM5		Ancient quarrying area (Area 1; Fig. 4)	North of "Su Padru" and "Su Padricheddu"; south (near) of the Mulargia ancient road	4 460 335	1 482 870
MM6				4 460 245	1 482 795
MM23				4 460 250	1 482 695
MM7				4 460 575	1 482 840
MM8		Ancient quarrying area (Area 3; Fig. 4)	South-west of the "Sa Tuppa"; north of the Provincial roadway N.62 Mulargia-Bortigali	4 460 600	1 482 880
MM10				4 460 675	1 482 850
MM12	Ignimbrite samples from Mulargia outcrops			4 460 255	1 483 230
MM13		Ancient quarrying area (Area 4; Fig. 4)	"Sa Perca"; south (near) of the Mulargia ancient road	4 460 320	1 483 320
MM14				4 460 465	1 483 235
MM20				4 460 470	1 483 385
MM22				4 460 355	1 483 595
MM19				4 460 565	1 482 475
MM24		Outcrops (Area 2; Fig. 4)	Mulargia village	4 460 520	1 482 500
MM25				4 460 535	1 482 540
DO49C3		*catillus* mount fragment	1.5 km south of Thugga	4 029552	518142
DO74.2		*catillus* rim fragment	1.8 km from Thugga	4 029679	521509
DO474		*catillus* (hand mill)	1 km to the north-east of Teboursouk	4 035180	522948
DO477	Millstones found in North Africa	*meta*	5 km to the north of Thibursicum Bure	4 037489	524768
DO500		*catillus* rim fragment	Hill-top at 3.7 km to the north-west of Thibursicum Bure	4 037514	519332
DO508		Non-reversible ring *catillus*	5.2 km to the north of Thibursicum Bure	4 038740	522937
DO536		*catillus* rim fragment	Kodiat an-Nemcha	4 035816	514717
DOSP.v		*catillus* mount fragment	Sporadic find from rural site	–	–

Table 2
Summary of the petrographic features of ancient millstones found in North Africa and of the representative ignimbrites from the three Mulargia quarrying areas.

Sample		Rock classification		Vesiculation (vol%)	Texture	P.I. (vol%)	Phenocrysts[a]	Groundmass	Secondary minerals[b]
Label	Type/Origin	Le Bas et al. 1986	De La Roche et al. 1980						
MM3		K-Rhy	Rhy	25–27	Por, Gl-por	8–9	Opq, Pl, ± Kfs ± Opx ± Cpx, ± Hbl ± Bt	hypohyaline –vitrophyric, fluidal	Phy, Kfs, Qtz
MM6	Field	K-TrDa	Rhy	12–14	Por, Gl-por	15–16	Opq, Pl, ± Kfs ± Opx ± Cpx, ± Hbl ± Bt	hypohyaline, fluidal	Kfs, Qtz, Phy
MM23	Area 1	K-Rhy	Rhy	20–22	Por, Gl-por	14–16	Opq, Pl, Opx ± Cpx	hypohyaline, fluidal	Kfs, Qtz, Phy
MM24	Area 2	K-TrDa	Rhy	16–18	Por, Gl-por	15–16	Opq, Pl, ± Kfs ± Opx ± Cpx	hypohyaline, fluidal	Kfs, Qtz, Phy
MM25	Area 2	K-TrDa	Rhy	18–20	Por, Gl-por	12–14	Opq, Pl, ± Kfs ± Opx ± Cpx, ± Hbl	hypohyaline –vitrophyric, fluidal	Kfs, Qtz, Phy
MM7	Field	K-TrDa	Rhy	18–20	Por, Gl-por	12–13	Opq, Pl, ± Kfs ± Opx ± Cpx	hypohyaline –vitrophyric, fluidal	Kfs, Qtz
MM8	Area 3	K-TrDa	Rhy	13–15	Por, Gl-por	11–13	Opq, Pl, ± Kfs ± Opx ± Cpx	hypohyaline, fluidal	Kfs, Qtz
MM12		K-Rhy	Rhy	20–22	Por, Gl-por	14–15	Opq, Pl ± Opx ± Cpx	hypohyaline –vitrophyric, fluidal	Kfs, Qtz
MM13	Field	K-TrDa	Rhy	8–10	Por, Gl-por	13–14	Opq, Pl, ± Kfs ± Opx ± Cpx	hypohyaline –vitrophyric, fluidal	Phy, Kfs, Qtz
MM14	Area 4	K-TrDa	Rhy	26–28	Por, Gl-por	12–14	Opq, Pl, Opx ± Cpx	hypohyaline, fluidal	Kfs, Qtz, Phy
MM20		K-TrDa	Rhy	18–20	Por, Gl-por	9–11	Opq, Pl ± Opx ± Cpx	vitrophyric, fluidal	Kfs, Qtz
MM22		K-TrDa	Rhy	22–24	Por, Gl-por	16–18	Opq, Pl ± Kfs ± Opx ± Cpx	hypohyaline, fluidal	Kfs, Qtz, Phy
49C3		K-TrDa	Rhy-Da	18–20	Por, Gl-por	11–12	Opq, Pl, Opx ± Cpx	hypohyaline, fluidal	Phy, Qtz, Kfs
74.2		K-TrDa	Rhy	26–28	Por	8–10	Opq, Pl ± Opx ± Cpx	vitrophyric, fluidal	Kfs, Qtz
474		K-Da	Rhy-Da	17–19	Por, Gl-por	12–14	Opq, Pl, Opx ± Cpx	hypohyaline, fluidal	Kfs, Qtz, Phy
477		K-TrDa	Rhy-Da	16–18	Por, Gl-por	16–18	Opq, Pl, Opx ± Cpx ± Hbl ± Bt	hypohyaline, fluidal	Phy, Kfs, Cal
500	Millstones	K-TrDa	Rhy-Da	14–16	Por, Gl-por	8–10	Opq, Pl, Opx ± Cpx ± Hbl ± Bt	hypohyaline, fluidal	Kfs, Qtz
508		K-TrDa	Rhy	16–18	Por, Gl-por	15–17	Opq, Pl, Opx ± Cpx ± Hbl ± Bt	hypohyaline, fluidal	Phy, Kfs, Cal
536		K-TrDa	Rhy	18–20	Por, Gl-por	13–15	Opq, Pl ± Opx ± Cpx ± Hbl ± Bt	hypohyaline-vitrophyric, fluidal	Kfs, Qtz, Phy
DOSP.v		K-TrDa	Rhy-Da	17–19	Por, Gl-por	14–16	Opq, Pl, ± Kfs ± Opx ± Cpx ± Hbl ± Bt	hypohyaline-vitrophyric, fluidal	Phy, Cal

Legend of abbreviations: Hbl = Hornblende; Bt = biotite; Cal = calcite; Cpx = clinopyroxene; Kfs = K-feldspar (sanidine); Opq = opaque; Opx = orthopyroxene; Phy = phyllosilicates (*e.g.*, celadonite, clinochlore, etc.); Pl = plagioclase; Qtz = quartz; Por = porphyritic; Gl-por = glomerporphyritic; K-Rhy = potassic rhyolite: K-TrDa = potassic trachydacite; K-Da = potassic dacite; Rhy = rhyolite; Rhy-Da = rhyodacite.

[a] Minerals reported in order of segregation.

[b] minerals reported in order of abundance.

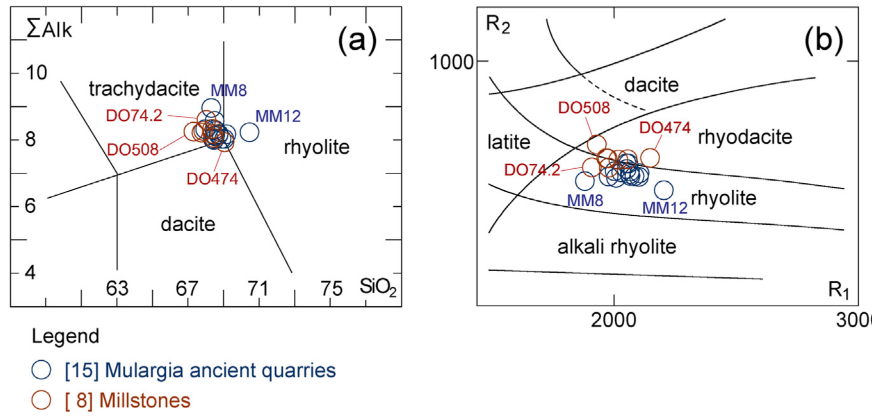

Fig. 9. Petrographic classification of both the ignimbrites from the Mulargia quarrying area and samples of ancient millstones found in Tunisia using the (a) the Total Alkali *vs.* Silica scheme (Le Bas et al., 1986; modified) and (b) R_1 *vs.* R_2 diagram of De La Roche et al., 1980 (modified).

A brief description of the farm sites and the eight volcanic mills investigated for this work is reported below (Table 1; Figs. 7 and 8). The lava exploited for the millstones selected shows the characteristic macroscopic aspect of the products from Mulargia (red-brown ignimbrites with many small vesicles lined with green phyllosilicates) which are not exhibited by the felsic volcanics (rhyolites) belonging to the Tunisian post-collisional calcalkaline magmatism (Halloul and Gourgaud, 2012 and references therein).

Farm site DO49 [518142 E, 4029552 N, 553-563 H]: it occupies a surface of 4780 m^2 covered with buildings (de Vos et al., 2013). It lies 1.5 km to the south-west of Thugga, on a steep slope, near the Ain Hammam-Thugga acqueduct. It is one of the biggest of the farms discovered in the vicinity of Thugga and Thibursicum Bure. It was occupied from the Pre-Roman periods until the end of the Byzantine domination (AD 650–700). It had a spring (Ain en-Naia) at its disposal, and was equipped with four oil or wine presses, four cisterns, four 'donkey' *catilli* (two of red lava and two of black lava), two *molae manuales* of local stone (one of white nummulitic limestone and the second of a different fossiliferous limestone), it had a room or basin paved with white mosaic and tiles of *marmor carystium* from Euboea (Greece) among the scattered finds.

Dimensions of the *catillus* mount fragment analysed: h 12.5 cm; Ø mount mortise 3 cm.

Farm DO74.2 [521509 E, 4029679 N, 383 H]: located 1.8 km from Thugga, near Oued Djafer, which falls down Kef Thugga, it is equipped with a press and a cistern of two *camerae* (de Vos et al., 2013).

Dimensions of the *catillus* rim fragment analysed: h 11 cm, thickness 3.5 cm.

Farm site DO474 [522948 E, 4035180 N, 381 H]: located 1 km to the north-east of Teboursouk it was destroyed during the digging of a pit in 1995, when elements of an oil or wine press were discovered, together with this half part of a *catillus* or runner of a hand mill of red lava. The *catillus* is lopsided as it is worn from intensive use.

Dimensions of the hand mill analysed: Ø 31 cm; h 8.7 cm; Ø central orifice 9 cm; rynd mortice 2.5 × 3 × 2.2 cm, containing lead.

Farm site DO477 [524768 E, 4037489 N, 414 H]: located 5.2 km to the north of Thibursicum Bure, not far from the ancient Carthago-Tichilla-Thibursicum Bure-Sicca Veneria road, it was built on top of an artificial terrace situated on a slope near the mountain top of Djebel Slagwa; it has a press and a tombstone commemorating Kanin[i]us Maius (de Vos et al., 2013). Four other Caninii are attested in other sites, all to the north of Thibursicum Bure. They may derive their *gentilicium* from C. Caninius Rebilus, proconsul of Africa in 46 BC, or from his son C. Caninius Gallus, consul with Agrippa in 37 BC or from another son, also called C. Caninius Rebilus, who was consul in 2 BC and proconsul of Africa from AD 2–6. The upper part of a *meta* of red lava was found on the surface; its inside is hollowed in order to diminish its weight, in order to facilitate its transport.

Dimensions of the *meta* analysed: h 24 cm, cone 15 cm, Ø cone 11.5 cm.

Farm site DO500 [519332 E, 4037514 N, 523 H]: it is located on a hill-top 3.7 km to the north-west of Thibursicum Bure (built-up area 2449 m^2); the farm was built of big rusticated blocks and equipped with two presses; it was altered and expanded in Late Antiquity (de Vos et al., 2013).

Dimensions of the analysed *catillus* rim fragment of red lava with polished inside surface: 7.5 × 4.5 cm.

Farm site DO508 [522937 E, 4038740 N, 467 H]: located 5.4 km to the north of Thibursicum Bure (near the Aïn Moungass spring) is a rather sophisticated farm: the outside face of the principal building consists of a framework of ashlar blocks (*opus africanum*) with filling in *opus reticulatum*; it contains a circular pit in *opus vittatum* and a private aqueduct (de Vos et al., 2013). The site contained a *meta* in nummulitic limestone and two *catillus* fragments of red lava. The fragmentary and short non-reversible ring analysed, *catillus* DU508 (dimensions: h 18.7 cm, width 15 cm, mount aperture size 9.5 × 6 × 5.5 cm) has its handle lug not in the centre of the external profile, but on the higher bottom cone; the lug has only 3 protruding sides, the upper side being open. The two superimposed cones are not of the same size, as in cases of both the mills of the Sec wreck,[2] and that found at Morgantina,[3] Carthage (under the *Decumanus Maximus*[4]) and Byrsa[5]: all these mills are non-reversible and they belong to the Hellenistic age. At Hippo Regius a similar fragment of red ignimbritic lava is displayed in the Museum garden.[6] A complete *catillus* at Rusicade (Skikda)[7] has similar slots.

Farm site DO536 [514717 E, 4035816 N, 605 H]: consists of at least six rooms and a cistern and it was built on the very steep slope of Kodiat an-Nemcha. The access was and still is rather difficult (de Vos et al., 2013). The *catillus* rim of red lava analysed has a thickness of 3.5 cm.

[2] Beltrame and Boetto 1997, 183, 185: n. 115.3, dated to 375–50 BC by amphorae, pottery and bronze finds on the wreck.

[3] de Vos *et al.*, 2011, 141–2, Fig. 2; White 1963; Sposito 2008, *passim*, pl. XLIII–XLIV, dated to the 3rd century BC; Santi *et al.*, 2013.

[4] Niemeyer et al., 2007, p. 771, n°6238 Taf. 52: red lava, Ø 29 cm, datable late III c.-first half of the II c. B.C.

[5] Lancel 1982, ca. 150 BC.

[6] Antonelli *et al.*, 2009; Antonelli *et al.*, 2010.

[7] Delamare 1850, pl. 160.11 and 12.

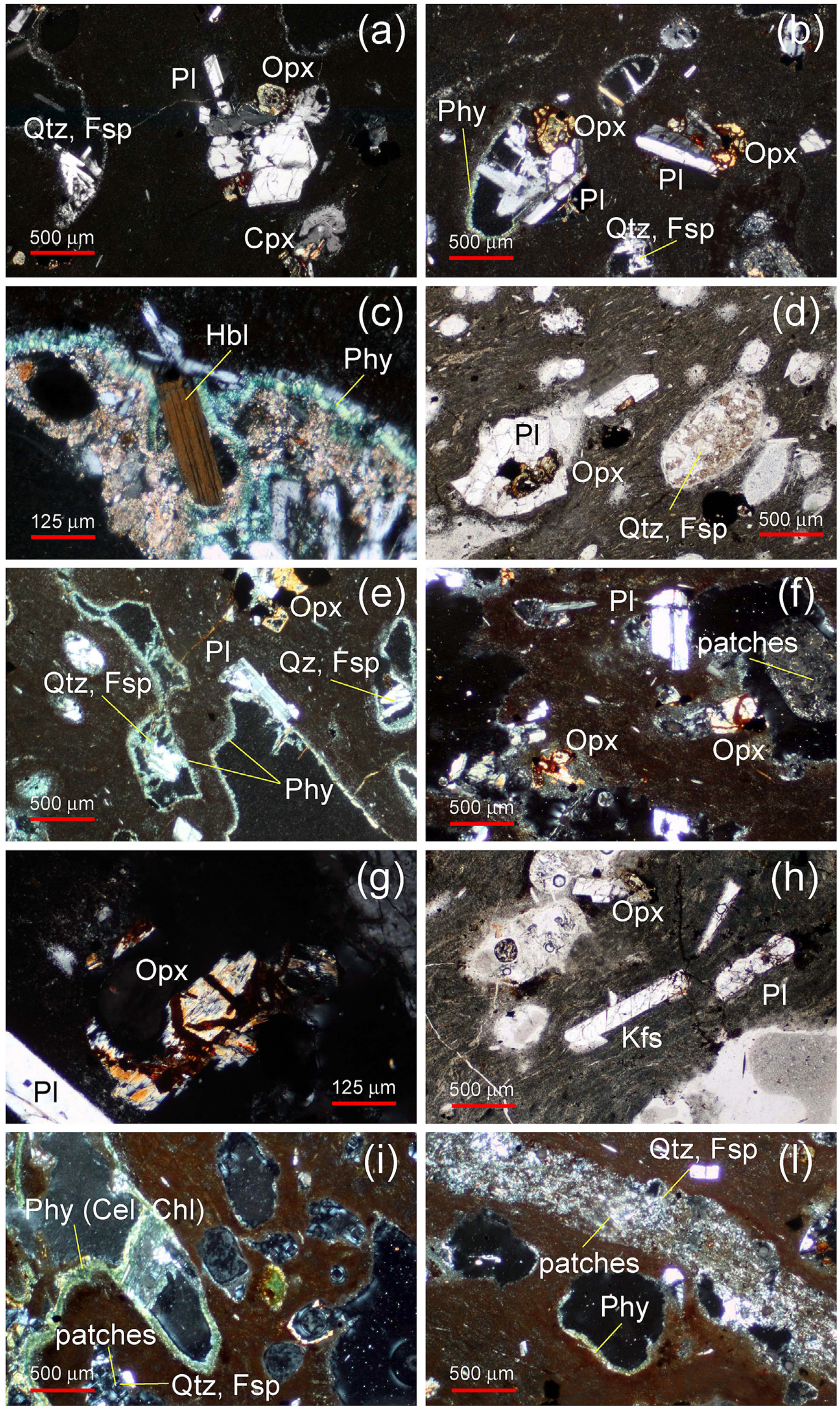

Fig. 10. Photomicrographs of thin sections of both the millstones found in Tunisia (a, b, c, d, e) and field samples from Mulargia ancient quarrying area and outcrops (f, g, h, i, l). (a) DO500 millstone: glomeroporphyritic assemblage of plagioclase and orthopyroxene (at the centre) with quartz-feldspar mineral aggregate inside a cavity (on the left). (b) DOSP.v millstone: glomeroporphyritic assemblage of plagioclase and orthopyroxene and vesicles with quartz-feldspar aggregate and orthopyroxene. (c) DOSP.v millstone: hornblende and quartz-feldspar mineral aggregate inside a miarolitic cavity with green deposits of celadonite (Phy). (d) DO477 millstone: glomeroporphyritic assemblage of plagioclase and orthopyroxene (on the left) with quartz-feldspar mineral aggregate inside a miarolitic cavity (on the right). (e) DO49C3 millstone: cavities with green phyllosilicate deposits on their inner surfaces. (f) MM6 sample: orthopyroxene phenocrysts into a glassy groundmass with fluidal texture. (g) MM6 sample: oxidized phenocryst of orthopyroxene. (h) MM23 sample: K-feldspar, plagioclase and orthopyroxene phenocrysts in a groundmass with eutaxitic/fluidal texture. (i) MM3 sample: vesicles with green phyllosilicate (celadonite + clinochlore) deposits on their inner surfaces and a cavity with quartz-feldspar aggregate (on down). (l) MM14 sample: quartz-feldspar mineral aggregate inside a miarolitic cavity with phyllosilicate minerals. Legend: (abbreviations of minerals after Kretz, 1983) Cel = celadonite; Chl = clinochlore (chlorite); Cpx = clinopyroxene; Hbl = hornblende; Kfs = K-feldspar (sanidine); Opx = orthopyroxene; Phy = celadonite and clinochlore phyllosilicates; Pl = plagioclase; Qtz = quartz; Patches = patches of devitrified glass. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3a
Whole-rock major (wt%) elements, C.I.P.W. norm, D.I., SAL, FEM.

Sample	Field samples									
	MM3	MM5	MM6	MM7	MM8	MM10	MM12	MM13	MM14	MM19
(wt %)										
SiO_2	69.03	68.39	68.45	68.49	68.30	68.51	70.45	68.88	68.48	68.71
TiO_2	0.61	0.62	0.61	0.63	0.63	0.64	0.48	0.64	0.62	0.62
Al_2O_3	14.97	15.30	15.21	15.23	15.20	15.60	15.27	15.30	15.30	15.17
Fe_2O_3(t)	4.52	4.50	4.55	4.48	4.46	4.62	3.67	4.58	4.45	4.45
MnO	0.14	0.13	0.10	0.11	0.11	0.12	0.09	0.15	0.10	0.09
MgO	0.36	0.39	0.49	0.40	0.34	0.23	0.25	0.28	0.38	0.35
CaO	2.15	2.46	2.42	1.96	1.82	1.99	1.50	1.99	2.16	2.28
Na_2O	4.01	4.10	4.12	3.72	3.67	3.85	3.79	3.93	4.02	4.05
K_2O	4.02	3.93	3.88	4.85	5.29	4.26	4.44	4.10	4.29	4.10
P_2O_5	0.18	0.16	0.16	0.13	0.18	0.17	0.06	0.14	0.19	0.17
LOI	1.69	1.33	1.61	1.52	1.46	1.58	1.51	2.03	2.12	1.39
CIPW norm (Fe_2O_3/FeO = 0.5)										
Quartz	23.23	21.68	21.73	21.48	20.44	23.21	26.01	23.57	21.69	22.17
Calcite	0.54	0.21	0.22	0.61	0.56	1.44	1.65	1.11	0.57	0.33
Orthoclase	23.76	23.22	22.93	28.66	31.26	25.18	26.24	24.23	25.35	24.23
Albite	33.93	34.69	34.86	31.48	31.05	32.58	32.07	33.25	34.02	34.27
Anorthite	9.49	11.16	10.96	8.87	7.85	8.76	7.05	8.96	9.47	10.20
Diopside	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hedenbergite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Enstatite	0.90	0.97	1.22	1.00	0.85	0.57	0.62	0.70	0.95	0.87
Ferrosilite	5.39	5.31	5.36	5.23	5.20	5.44	4.36	5.42	5.12	5.18
Hypersthene	6.29	6.28	6.58	6.22	6.05	6.01	4.98	6.12	6.07	6.06
Magnetite	0.78	0.78	0.78	0.77	0.77	0.80	0.63	0.79	0.77	0.77
Illite	1.16	1.18	1.16	1.20	1.20	1.22	0.91	1.22	1.18	1.18
Apatite	0.42	0.37	0.37	0.30	0.42	0.39	0.14	0.32	0.44	0.39
D.I.	80.92	79.60	79.52	81.62	82.76	80.96	84.32	81.06	81.06	80.67
SAL	90.95	90.97	90.70	91.10	91.17	91.17	93.01	91.13	91.10	91.20
FEM	8.64	8.62	8.89	8.51	8.45	8.42	6.66	8.46	8.53	8.40

Legend abbreviations: D.I. (differentiation index) = normative Quartz + Albite + Orthoclase + Nefeline + Kaliophilite + Leucite (Thornton and Tuttle, 1960); SAL = sum of sialic minerals; FEM = sum of mafic minerals.

Table 3b
Trace elements (ppm) of both the ignimbrites from the Mulargia quarrying areas and the studied ancient millstones found in Tunisia.

Sample	Field samples									
	MM3	MM5	MM6	MM7	MM8	MM10	MM12	MM13	MM14	MM19
(ppm)										
Sc	15.2	15.3	15.1	15.4	15.3	15.3	13.5	15.5	15.1	15.3
V	36	40	36	27	34	37	11	38	40	36
Cr	<1	<1	<1	6	<1	<1	<1	<1	<1	<1
Co	5	7	6	7	5	5	5	5	5	4
Ni	5	2	2	3	3	5	4	2	2	2
Cu	5	5	2	10	7	4	8	12	4	5
Zn	74	74	74	87	72	81	74	85	79	77
Rb	130	110	140	130	150	170	120	180	140	150
Sr	164	181	176	158	145	161	136	170	168	169
Ba	482	501	485	479	476	480	537	556	486	468
Y	37	40	43	41	32	45	38	36	39	33
Zr	207	207	204	202	188	213	235	210	213	205
La	34	30	36	39	31	40	34	30	35	28
Ce	39	49	47	44	46	48	54	37	51	36
Nd	22	20	11	31	20	38	29	24	19	32
Sm	3.3	3.3	3.3	3.1	3.0	3.8	3.8	3.6	3.4	3.4
Eu	1.5	1.7	1.8	1.9	1.8	1.8	1.8	1.9	2.3	<0.1
Tb	<0.5	<0.5	<0.5	1.1	<0.5	1.8	<0.5	1.3	<0.5	<0.5
Yb	3.8	4.0	4.6	4.6	3.6	4.4	4.5	4.3	4.8	3.8
Lu	0.7	0.8	0.8	0.7	0.7	0.8	0.8	0.8	0.7	0.7
Hf	5.5	5.4	5.8	5.3	5.8	5.8	7.8	6.0	5.7	5.9
Ta	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Th	8.6	8.5	8.3	7.6	7.8	8.4	9.3	8.9	7.8	8.6
U	<0.5	2.4	3.4	<0.5	2.6	3.2	1.9	2.2	2.8	2.6
$[La/Yb]_N$	5.9	5.0	5.2	5.6	5.7	6.1	5.0	4.6	4.8	4.9

					Millstones							
MM20	MM22	MM23	MM24	MM25	DO49C3	DO74.2	DO474	DO477	DO500	DO508	DO536	DOSP.v
(wt %)												
68.72	67.96	69.15	68.55	68.52	68.45	68.03	69.05	67.85	67.75	67.30	68.35	68.38
0.62	0.66	0.59	0.62	0.63	0.63	0.63	0.61	0.62	0.64	0.61	0.61	0.61
15.36	15.87	15.33	15.26	15.46	14.96	15.18	14.66	15.14	15.32	15.13	14.99	14.92
4.24	4.80	4.13	4.52	4.58	4.38	4.61	4.23	4.76	4.73	4.46	4.76	4.42
0.11	0.09	0.10	0.12	0.10	0.11	0.11	0.10	0.11	0.12	0.11	0.14	0.11
0.55	0.28	0.39	0.37	0.42	0.71	0.33	0.50	0.35	0.37	0.47	0.24	0.43
2.06	1.85	1.96	2.13	2.00	2.53	2.35	2.73	2.70	2.65	3.17	2.42	2.65
3.93	3.59	4.06	3.90	3.83	4.06	3.95	3.92	3.97	3.97	4.09	4.05	4.10
4.25	4.73	4.11	4.37	4.31	4.00	4.65	4.01	4.30	4.25	4.16	4.28	4.08
0.17	0.16	0.18	0.16	0.16	0.18	0.17	0.19	0.20	0.20	0.50	0.15	0.29
1.98	1.86	2.05	1.53	2.01	3.24	0.98	1.87	1.42	1.24	1.99	1.51	1.73
CIPW norm ($Fe_2O_3/FeO = 0.5$)												
22.60	22.50	23.36	22.05	22.84	21.35	19.88	22.99	20.28	20.28	19.52	20.90	21.27
0.96	1.86	1.07	0.62	1.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25.12	27.95	24.29	25.83	25.47	23.64	27.48	23.70	25.41	25.12	24.58	25.29	24.11
33.25	30.38	34.35	33.00	32.41	34.35	33.42	33.17	33.59	33.59	34.61	34.27	34.69
9.11	8.13	8.55	9.52	8.88	10.78	9.96	10.56	10.79	11.43	10.64	10.08	10.26
0.00	0.00	0.00	0.00	0.00	0.14	0.08	0.34	0.17	0.06	0.32	0.09	0.17
0.00	0.00	0.00	0.00	0.00	0.36	0.44	1.16	0.96	0.30	1.26	0.74	0.70
0.00	0.00	0.00	0.00	0.00	0.51	0.52	1.50	1.13	0.36	1.58	0.83	0.86
1.37	0.70	0.97	0.92	1.05	1.70	0.79	1.09	0.79	0.90	1.02	0.56	0.99
4.92	5.59	4.78	5.34	5.36	4.92	5.17	4.28	5.11	5.41	4.56	5.30	4.81
6.29	6.29	5.75	6.26	6.41	6.62	5.95	5.37	5.90	6.30	5.59	5.86	5.80
0.73	0.83	0.71	0.78	0.79	0.76	0.79	0.73	0.82	0.82	0.77	0.82	0.76
1.18	1.25	1.12	1.18	1.20	1.20	1.20	1.16	1.18	1.22	1.16	1.16	1.16
0.39	0.37	0.42	0.37	0.37	0.42	0.39	0.44	0.46	0.46	1.16	0.35	0.67
80.97	80.83	82.00	80.87	80.72	79.35	80.78	79.85	79.28	78.99	78.71	80.47	80.08
91.04	90.82	91.62	91.02	90.84	90.13	90.74	90.42	90.07	90.42	89.35	90.55	90.33
8.61	8.74	8.04	8.58	8.77	9.50	8.88	9.22	9.52	9.17	10.27	9.03	9.28

					Millstones							
MM20	MM22	MM23	MM24	MM25	DO49C3	DO74.2	DO474	DO477	DO500	DO508	DO536	SP.v
(ppm)												
14.9	15.8	14.7	15.3	15.9	13.9	15.6	15.2	16.0	16.5	15.7	14.7	13.0
31	35	27	35	34	35	34	38	39	38	43	44	43
<1	<1	<1	6	<1	<1	<1	<1	<1	<1	<1	<1	<1
5	5	5	5	5	<1	6	5	4	6	5	7	6
2	3	2	3	2	3	4	3	3	3	3	5	4
5	10	4	5	8	5	9	5	11	8	10	6	5
73	76	70	77	75	75	77	68	81	87	81	74	73
140	140	80	138	144	90	160	170	110	80	70	130	80
158	149	157	164	157	180	167	169	180	190	189	182	186
467	455	489	483	486	467	491	471	487	519	470	538	518
38	36	31	39	36	32	33	41	34	35	35	34	33
208	202	205	203	209	193	203	204	197	199	178	201	195
36	36	28	35	32	27	28	34	28	30	30	30	25
48	36	31	45	44	50	46	47	40	36	49	46	45
30	35	35	23	<28	<5	24	36	15	27	18	22	26
3.9	3.5	3.4	3.3	3.6	3.7	3.2	4.0	2.7	3.3	3.1	3.1	3.0
2.2	1.5	1.8	1.8	1.9	1.7	1.3	1.8	1.7	1.9	1.9	1.7	1.7
1.2	<0.5	<0.5	<1.4	<1.2	<0.5	1.0	1.3	<0.5	<0.5	<0.5	<0.5	<0.5
4.1	4.0	3.6	4.2	4.2	3.7	3.9	4.3	3.8	3.8	4.1	4.1	3.3
0.7	0.6	0.7	0.8	0.7	0.6	0.7	0.7	0.6	0.7	0.6	0.6	0.6
5.9	5.6	6.6	5.6	6.1	5.9	6.1	6.5	4.5	6.0	5.4	6.4	4.9
<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
8.3	8.6	8.8	8.2	8.6	7.6	9.3	8.9	7.6	8.9	8.2	10.1	7.7
3.6	2.5	2.6	<2.9	<2.6	2.0	3.4	<0.5	2.7	2.4	2.5	<0.5	2.4
5.8	6.0	5.2	5.6	5.3	4.9	4.8	5.2	4.9	5.2	5.0	4.9	5.1

Finally, sample DOSP.v is a fragmentary mount of a non-reversible *catillus*, a random find in one of the rural sites of the surveyed area. As in the case of millstone DO508, its handle lug is not in the centre of the hourglass profile. The inside grinding surface is smoothed by the rotary movement on the *meta* surface.

Total preserved height 15 cm, width 12 cm, mount height 8 cm, width 6.5 cm, handle lug Ø 2.5 cm.

5. Sampling and analytical methods

A total of fifteen samples (labelled MM; Table 1), all belonging to lithotype 1 described above (Section 3), were collected from a few still preserved quarry faces, debris, abandoned blocks and unfinished artefacts (Fig. 6) found inside the identified quarrying area (12 samples) and from ignimbrite outcrops around the village of Mulargia (3 samples) with macroscopic aspect similar to the reddish-brown rock used for manufacturing the Roman millstones found in Mediterranean archaeological sites. The samples were collected mainly from four outcropping areas of lava-like ignimbrites (Table 1): the first corresponds to the area previously indicated by Williams-Thorpe (1988) and Williams-Thorpe and Thorpe (1989), just to the south/south-east of Mulargia (Area 1 on Fig. 5); the second (Area 2 on Fig. 5) is located within the village of Mulargia; the third is located immediately to the north/north-east of Mulargia (about 100–150 m to the north of the Mulargia-Bortigali road; Area 3 on Fig. 5), where several fragments of half-finished ancient millstones were found; the fourth is located about 1 km to the east of the village of Mulargia (Area 4 on Fig. 5), where stepped blocks, wedge-holes and pick marks were found (Fig. 6a–d).

Modal mineralogy and petrographic textures of twelve selected samples from the four main quarrying areas (Areas 1–4 in Fig. 5) were investigated by optical microscopy (OM).

Whole-rock chemistry of all the field samples was determined on selected portions (avoiding the larger miarolitic cavities) at the Activation Laboratories LTD (Ancaster, Canada). Samples were melted using lithium metaborate/tetraborate and dissolved with HNO_3. Major elements were analysed by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) using a Thermo Jarrell-Ash ENVIRO II ICP, whereas trace elements were determined by Inductively Coupled Plasma- Mass Spectrometry (ICP-MS) with a Perkin Elmer SCIEX ELAN 6000 ICP-MS. The degree of uncertainty is less than 3% for major oxides, less than 5% for Rb, Sr, Zr, Y, V, Hf and the REE, from 5 to 10% for all other trace elements. More information on the precision and accuracy of the method is available at www.actlabs.com.

The same method (OM + ICP-OES/MS) was then applied to eight samples (40 g each) of the Roman millstones described above (labelled DO; Table 1) which were collected from the eight Numidian rural archaeological areas described previously (Section 4).

6. Results

6.1. Petrography and geochemistry of the Mulargia ignimbrites

The main petrographic features of the source rocks considered here are noted in Table 2. According to the classification diagrams proposed by Le Bas et al. (1986; Fig. 9a) and De La Roche (1980; Fig. 9b) all the Mulargia ignimbrites collected within and around the quarrying areas identified are classified as trachydacites and rhyolites in the first case, or fall essentially at the limit with the rhyolite and rhyodacite fields in the second one, in good agreement with the modal mineralogy.

These rocks are characterized by porphyritic and glomeroporphyritic textures (porphyritic index – hereafter P.I. – between 8% and 16%; Table 2) with a common mineralogical assemblage represented by phenocrysts and micro-phenocrysts of plagioclase (often dusty), orthopyroxene ± clinopyroxene ± K-feldspar (sanidine) in paragenetic sequence, with early segregation of Fe–Ti oxides (Fig. 10). Xenoliths are rare and represented mainly by cognate fragments and crystal-clasts of plagioclase.

The plagioclase is often dusty and the presence of Ca-plagioclase relics decreases, modally and also in size, passing from the dacitic members to the rhyolitic ones. Among the ortho- and clino-pyroxenes, hyperstenic and augitic terms prevail (optical determination). Hornblende (optical determination) occurs in rhyolitic samples with the occasional presence of elongated flakes of biotite (*i.e.*, samples MM3, MM6; Table 2).

The groundmass is commonly glassy, from vitrophyric to hypohyaline (Fig. 10), only occasionally cryptocrystalline, with rare microliths of apatite and opaque minerals. It is often characterized by a reddish colour due to high temperature oxidation of iron and shows eutaxitic (especially in the most massive and welded facies) or fluidal textures (Fig. 10; Table 2). Some samples exhibit sub-

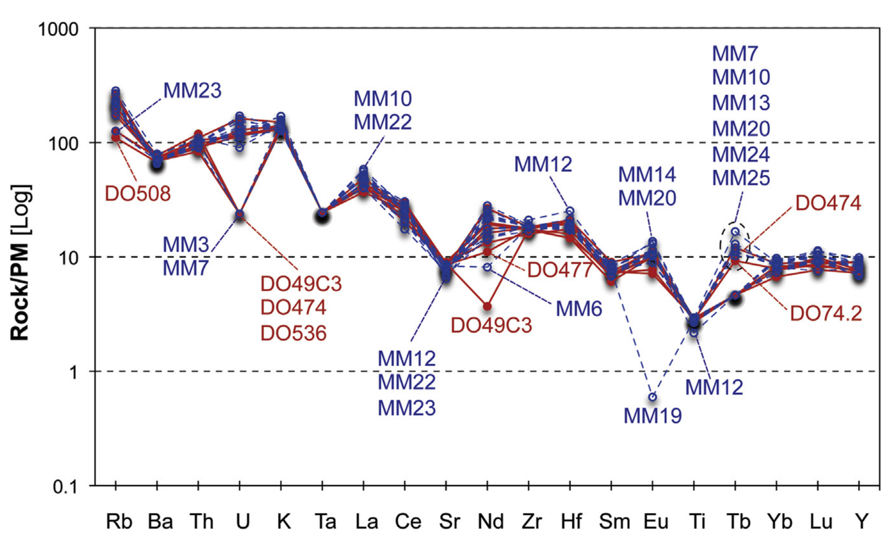

Fig. 11. Incompatible trace–elements diagram normalized to (PM) primordial mantle (according to Sun and McDonough, 1989) for samples from both the Mulargia quarrying areas and archaeological sites in Tunisia (millstones). The analysed values of Ta were below the measure limit (1 ppm) for all the samples. In order to draw the diagram the concentration of this element has been arbitrarily considered 0.99 ppm for each sample.

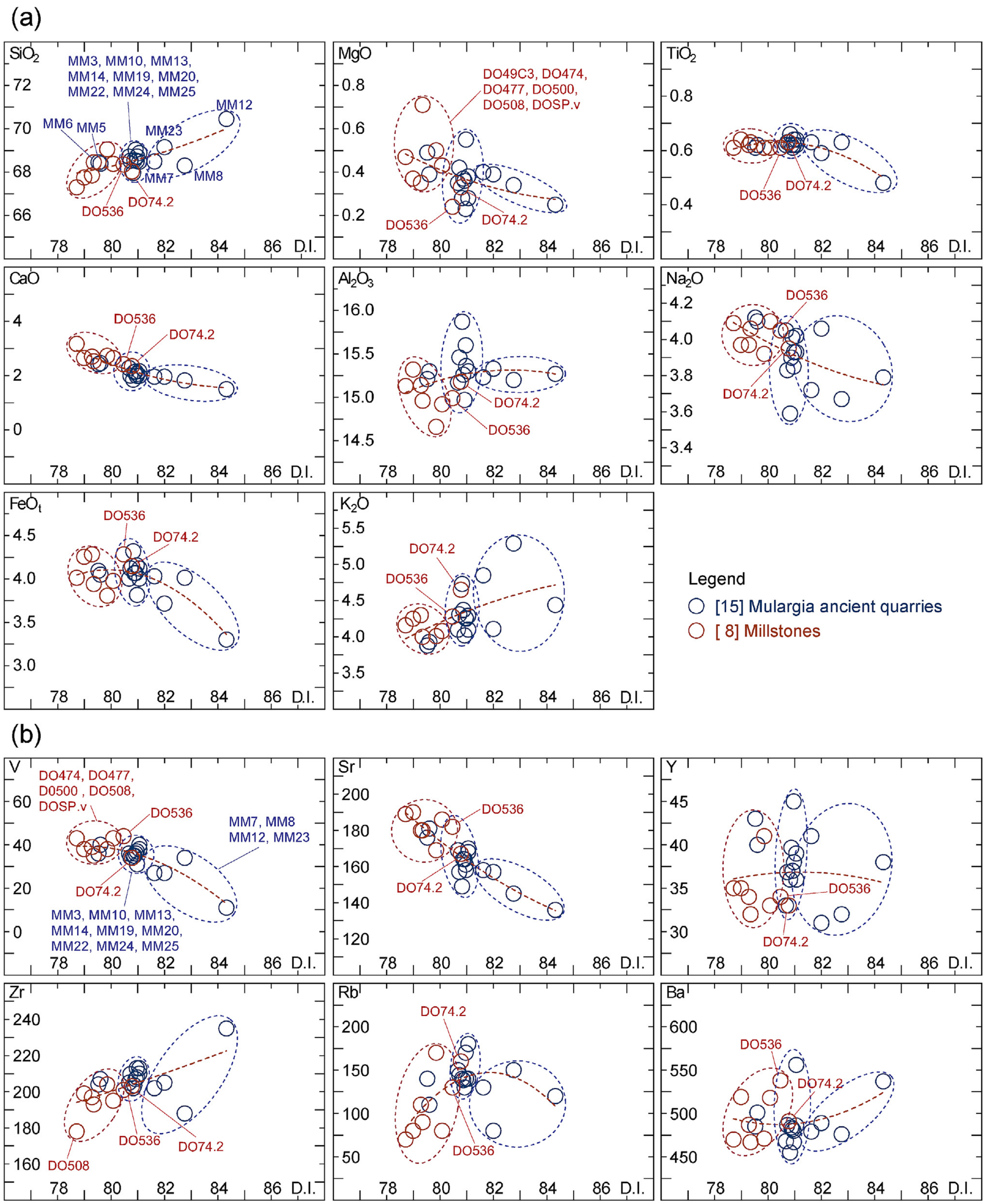

Fig. 12. Variation diagrams: differentiation index (D.I.) *versus* (a) major elements (expressed as %) and (b) trace elements (expressed as ppm) for both the Mulargia ignimbrites and Hellenistic and Roman millstones found in Tunisia.

millimetre pseudo-elliptical or elongated patches of devitrified glass characterized by the recrystallization of sub-radial growth quartz and feldspar microliths (MM6, MM3, Fig. 10f and i; MM14, Fig. 10l), with the occasional presence of biotite, hornblende and microcrystalline calcite in miarolitic cavity. On the inner surface of the vesicles, celadonite and clinochlore microcrystals (whose presences were detected by XRD analysis) were also observed (Fig. 10i).

With regard to the geochemistry, all the samples examined are silica saturated products (SiO_2 66–69%) with normative

Quartz (19.74–25.50 wt%) and *Hypersthene* (4.90–6.43 wt%) in the C.I.P.W. composition (Table 3a). They show a subalkaline, high–K calk-alkaline affinity like most of the analogous rocks belonging to the Oligo-Miocenic Mulargia-Macomer-Bortigali volcanic district. Only three samples (MM22, MM7 and MM8) exhibit a K_2O relatively higher content (4.60, 4.76, 5.11 wt%, respectively) with regard to the others (for which K_2O 3.79–4.36 wt%), probably due to the presence of sanidine feldspar among the phenocrysts and to the higher occurrence of phyllosilicates into the micro-vesicles.

The chemical compositions of all the samples collected are, in general, quite homogeneous, without any significant variation for the most part of major and trace elements (Figs. 11 and 12 and Table 3a and b): SiO_2 65.97–69.13%, Al_2O_3 14.47–15.43%,[8] TiO_2 mainly $\geq$0.6% (0.47–0.64%), K_2O/Na_2O ratio roughly around 1 (0.94–1.44), $K_2O + Na_2O$ generally $\geq$ 8% (7.77–8.65%), Rb 80–180 ppm, Zr 188–235 ppm, and low concentrations of Cr ($\leq$1–6 ppm), Co ($\leq$7 ppm) and Y (31–45 ppm).

A very slight and quite regular enrichment of light rare earths is displayed, $[La/Yb]_N$ varying from 4.6 to 6.1. Incompatible trace elements normalized to primordial mantle (according to Sun and McDonough, 1989) are reported in the spiderdiagram of Fig. 10, in which all the samples share a typical orogenic-type outline characterized by clear Ta- and Ti-negative anomalies as a consequence of the fractionation of Large Ion Lithophile (LIL) elements with respect to High Field Strength (HFS) elements (Hoefs, 2010). These anomalies are compatible with a provenance from subduction-related magmatic series.

These data extend the reference chemical values summarized previously by Antonelli and Lazzarini (2010) on the basis of the very few samples analysed by Williams-Thorpe (1988) and Williams-Thorpe and Thorpe (1989).

6.2. Petrography and geochemistry of archaeological finds

The mineralogical characteristics and textures of the eight millstone fragments are very similar to each other and have strong analogies with those observed in the ignimbrites from the Mulargia quarrying area (Fig. 10; Table 2). On a macroscopic scale they look like reddish-brownish lava-like ignimbrites and show medium–high degrees of welding and vesiculation, the latter often oriented.

On the basis of the microscopic features and chemical data (Tables 2 and 3; Figs. 9–13) these rocks belong to a subalkaline, high–K calkalkaline series and may be classified as porphyritic (P.I. 8–18%; Table 2) rhyodacites and rhyolites (Fig. 9b) or trachydacites (Fig. 9a) according to the classification schemes proposed by De La Roche et al. (1980) and Le Bas et al. (1986), respectively.

Plagioclase (sometimes with a strongly calcic inner part of the relic) is the most abundant phase among phenocrysts with the restricted occurrence of both subhedral augite and euhedral hyperstene pyroxenes, which sometimes form glomeroporphyritic textures with the former. Sanidine, hornblende and biotite may occur among the phenocrysts of the rhyolitic terms (DO477, DO500, DO536, DOSP.v; Table 2), whereas opaque minerals (magnetite) are generally accessory micro-phenocrysts.

The groundmass (Fig. 10d and h) is mainly glassy (sometimes with devitrified glass patches including quartz-feldspar aggregate minerals; Fig. 10a–e), from hypohyaline to vitrophyric, and may include microliths of quartz and acicular plagioclase oriented according to the flow direction (fluidal texture). Vesicles are very often lined with typical green phyllosilicates (celadonite + clinochlore as detected by XRD analysis; Fig. 10c and e) with the occasional presence of microcrystalline calcite, biotite and hornblende (Fig. 10c).

The chemical compositions of the archaeological finds were carefully compared with those previously defined in the quarrying source group. All the millstones analysed in the present work have a strong chemical affinity with the Mulargia raw materials with which they share the same major and trace element trends (Table 3a and b; Figs. 9 and 11–13). In particular, according to the volcanics from the quarrying area, they exhibit very low concentrations of Cr (<1 ppm), Co (<7 ppm), and low contents of Rb (80–170 ppm), Y (32–41 ppm) and Zr (193–204 ppm). Only CaO concentrations are slightly higher than those recorded in the field samples, most likely as a consequence of protracted burial in the calcareous terrains of the Thugga region. This secondary enrichment of calcium also explains the absence of *Corindone* in the C.I.P.W. normative composition of the archaeological finds. The normalized trace-element spider-diagram patterns of the millstones (Fig. 11) compare closely with each other and virtually coincide with the pattern of the Mulargia ignimbrite outcrops. Furthermore, all the millstone samples plot perfectly within the Zr *vs.* Cr and Zr *vs.* V fields (Fig. 14) defined for the Mulargia ignimbrites by Williams-Thorpe (1988) and Antonelli and Lazzarini (2010; after Williams-Thorpe and Thorpe, 1989; modified), respectively. These diagrams differentiate the Mulargia raw materials both from other Sardinian Oligocene-Miocene and Pliocene-Pleistocene volcanics and from the main Mediterranean millstone source rocks exploited in Antiquity. Finally, on the basis of discriminant geochemical data, it is possible to make some suppositions about the exact provenance of the eight millstones within the context of the outcrops sampled around the Mulargia area. Excluding four field samples (MM 7, MM8, MM12, MM23) which show a degree of evolution significantly higher than all the others (differentiation index – herafter D.I. – over 81.5), most of the millstones (in particular DO49C3, DO474, DO477, DO500, DO508, DOSP.v) may be associated to samples MM5 and MM6 (Fig. 11) and probably come from field Area 1 (south of Mulargia; Fig. 5).

7. Conclusions

The main ancient quarry area yielding Mulargia volcanic rock millstones has been recognized and investigated. Fifteen field samples were collected to create a petrographic and geochemical databank designed to provide an effective tool for provenance

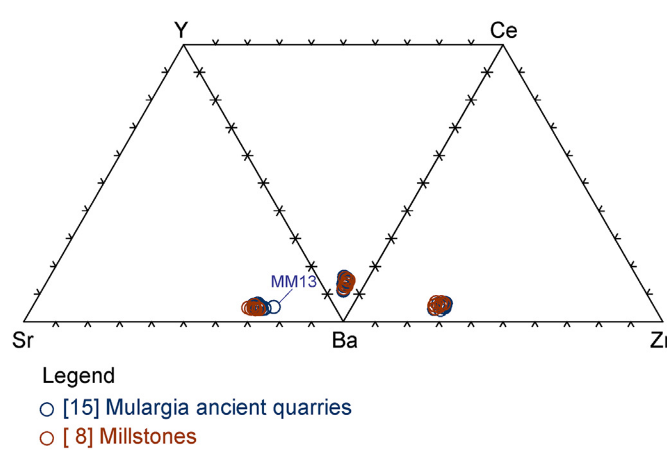

Fig. 13. Triangular diagrams of some significant trace elements for the Mulargia ignimbrites and investigated millstones found in Tunisia.

[8] The Al_2O_3 content is most probably slightly higher than expected because of the abundant presence of clinochlore into the vesicles.

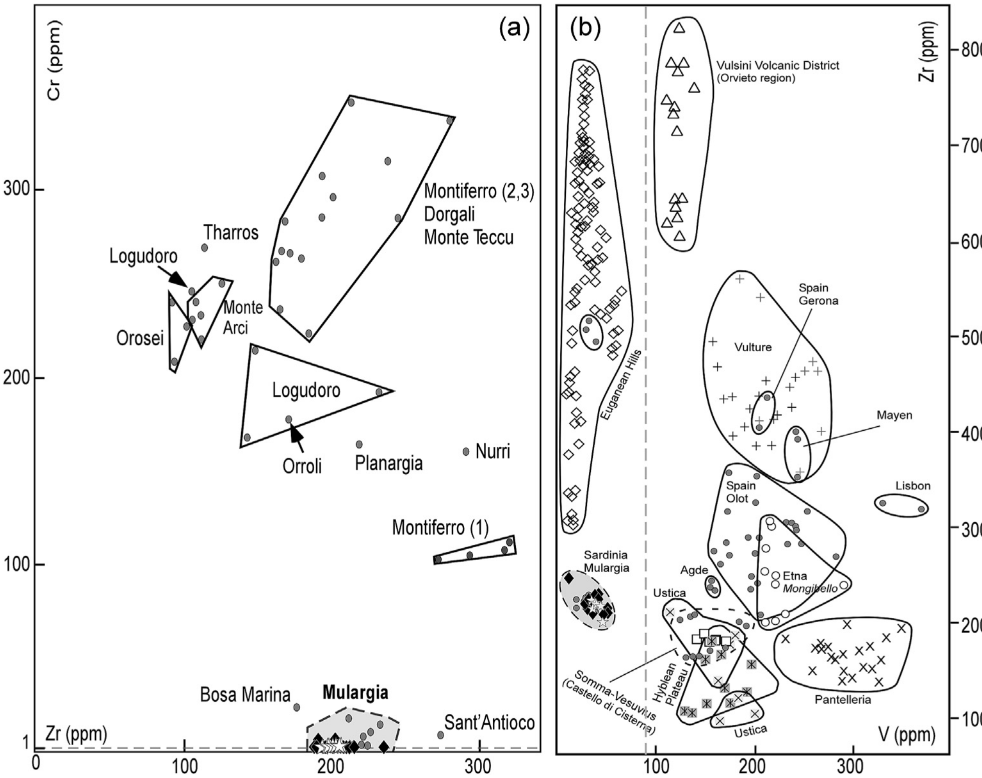

Fig. 14. (a): Zr *vs.* Cr showing Sardinian Pliocene basic-intermediate lavas and Oligocene-Miocene intermediate-acid rocks including the samples of Mulargia ignimbrites and millstones. After Williams-Thorpe, 1988, modified. (b): Discrimination among the main Mediterranean millstone source rocks using Zr *vs.* V diagram proposed by Williams-Thorpe (1988) and modified by Antonelli and Lazzarini (2010). The grey broken line separates the acid from the basic-to-intermediate rocks. Symbols: full diamond: Mulargia ignimbrites – this study; Star: Hellenistic and Roman millstones found in Tunisia – this study; Data and symbols of the geological samples of all the volcanic rocks other than Mulargia ignimbrites are from Williams-Thorpe, 1988 (full circles) and Antonelli and Lazzarini, 2010 (all the others). Data for comparison are from: Antonelli et al., 2001 and Buffone et al., 2000 (open triangles: leucite-bearing lavas from the Roman quarries of Orvieto, Vulsini Volcanic Discrict); Cristofolini et al., 1991 (empty circles: hawaiites and mugearites from Mt. Etna, Mongibello Recente); Buffone et al., 2000 (squares: leucite basaltic trachyandesites from Castello di Cisterna, Somma-Vesuvius); De Fino et al., 1986; Williams-Thorpe, 1988 and Beccaluva et al., 2002 (crosses: tephrites-foidites from Vulture Volcano; Capedri et al., 2000 (open diamonds: trachytic lavas from Euganean Hills); Civetta et al., 1984, 1998 (rotated crosses: alkaline and transitional basalts from the island of Pantelleria); Trua et al., 1998 (full grey asterisks: alkaline basalts from the Hyblean Plateau); Trua et al., 2003 (crossed squares: basic lavas of Ustica).

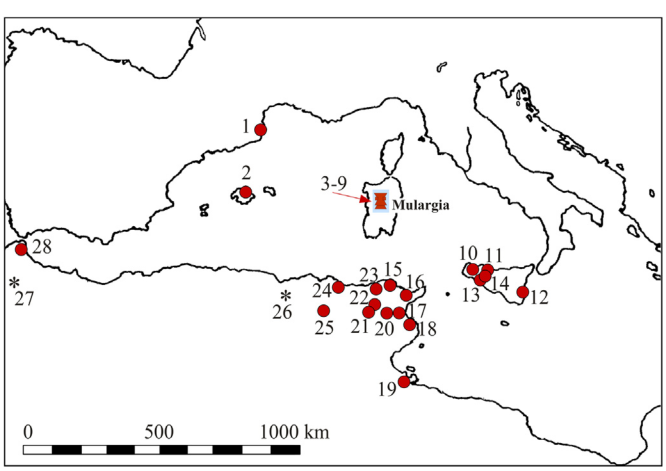

Fig. 15. Mediterranean distribution map of Hellenistic and Roman Mulargia millstones. After Williams-Thorpe and Thorpe (1989, 1991) with supplementary data after Antonelli and Lazzarini (2010) and de Vos et al. (2011). 1. Ampurias; 2. Pollentia; 3–9. Sassari museum; San Pietro di Sorres; Sant'Elena; Monte Zuighe; Sa Pattada; Mulargia; Tharros; 10. Segesta; 11. Solunto; 12. Megara Hyblea; 13. Selinunte; 14. Entella; 15. Utica; 16. Carthage; 17. Segermes; 18. Sousse Museum; 19. Gightis; 20. Thuburbo Maius; 21. Musti; 22. Thugga; 23. Thabraca; 24. Hippo Regius; 25. Tiddis; 26. Cuicul (Djemila; quick petrography); 27. Volubilis (quick petrography); 28. Tetouan museum.

discrimination. This database has been exploited to determine the origin of the volcanics used for eight Hellenistic and Roman millstones from several rural archaeological settlements in the Thugga region of Tunisia. The analytical data (by means of OM, ICP-OES/MS, XRD analysis) confirm a Sardinian origin from the Mulargia Oligo-Miocenic outcrops. As has been supposed in the past by archaeologists and archaeometrists (Williams-Thorpe, 1988; Williams-Thorpe and Thorpe, 1989; Antonelli and Lazzarini, 2010 with reference therein; de Vos et al., 2011), these results attest, for the first time on a clear analytical basis, the presence of Mulargia mills in North Africa, within a north–south axis of movement of grain-collecting ships. In particular, notwithstanding the distance of 100 km from the sea, heavy volcanic millstones from Mulargia were transported to the Thugga region, probably by boats and rafts on their way back up the Bagradas from Utica or Carthage after delivering oil/cereals/wine. In the same way many of the grain-collecting ships sailing from Carthage to Italy will have carried millstones as tradable ballast on their return voyage. In the Byrsa Museum garden sixty hand and hourglass shaped mills are on view: 37 of them are made of red rhyolithic ignimbrite lava (most probably from Mulargia), 7 of black lava (possibly from Sardinia[9])

[9] Most of the millstones made of black lavas found at Byrsa as well as in the other sites cited in the paragraph will be the subject of a forthcoming archaeometric research.

and 16 of local rock. So, 73% of the visible material was imported. Carthage had an important role as importer and distributor of Italic millstones (Peacock, 1980; Williams-Thorpe and Thorpe, 1989; de Vos et al., 2011).

The Segermes survey, 57 km south of Tunis, presents a similar situation: black and red lava account for 92% of all discovered mills (Dietz, 1995; Gerner Hansen, 1995, *passim*). In the Thugga region almost 60% of the mills were imported (28 of red ignimbritic lava, 14 of black lava), 40% are made of local nummulitic limestone (19) or other kinds of limestone (10) (de Vos et al., 2011), probably because of the close political and administrative links between Carthage and Thugga. Also the important grain exporting port of Hippo Regius (today Annaba, Algeria) displays at least eight imported lava mills (4 made of red ignimbrite, probably from Mulargia and 4 made of black basic lava). The relationship between Hippo Regius and its Numidian hinterland, the Subus plain, however, was not as intense as in the *pertica Carthaginiensium* and Numidia seems less permeable for imported volcanic mills because of the availability of local rocks, such as quartz conglomerate or quartz sandstone, suitable for grinding grain or compacting olives. The greater permeability of the *pertica* and surrounding regions can be attributed *inter alia* to the administrative and political relations between Carthage and Rome and the Byzantine Exarchate of Africa, of which Carthage was the capital and which also included Sardinia.

In conclusion, due to the mostly glassy matrix and the medium–high degree of welding combined with medium–high vesiculation, the Mulargia ignimbrites probably provided an optimal physical-mechanical performance through their good resistance to abrasion and a rough surface favourable to grinding. Probably as a result of these features, together with good workability and durability, the Mulargia millstones seem to have been better, in some way, or more highly prized than other mill typologies and lithologies and these qualities stimulated their widespread use in the south-western Hellenistic and Roman Mediterranean (Fig. 15), even in areas where suitable local lavas were available, such as Sicily (Selinunte, Entella, Segesta, Solunto and even Megara Hyblaea, near Mt. Etna; Williams-Thorpe, 1988; Daniele, 1997).

The distribution of Mulargia ignimbrite on such a large scale and as early as the 6th century BC is amazing, as the overland transport costs were high. Mulargia is 30 km from Bosa, 50 km from Cornus and 70 km from Tharros. Cato (De Agr. 22) compares the purchase price of a *trapetus* in the territory of Suessa, 25 miles from his villa at Venafrum, with that at Pompeii, 75 miles away, calculating transport costs. In the first case transport would represent 11% (72 sesterces) and in the second case 39% (280 sesterces). So even before being shipped the Mulargia mills were already expensive.

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